Assessment of Potential Mars Relay Network Enhancements

Charles D. Edwards, Jr., Roy Gladden, Charles H. Lee and Daniel Wenkert
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr
Pasadena, CA 91109
818-354-4408
Charles.D.Edwards@jpl.nasa.gov

Abstract— **In anticipation of increased demands on Mars relay services, including planned arrivals of NASA's InSight Lander in November 2018, and of NASA's Mars 2020 rover and ESA's ExoMars Rover & Surface Platform mission in Feb-Mar.2021, we have assessed a number of potential modifications and upgrades to Mars relay orbiters and quantified their impacts in terms of key relay support metrics, to support NASA and ESA programmatic decisions. Specific areas of investigation include: 1) implementation of "split-pass" relay capability for support to collocated landers, 2) modifications of the extended mission orbit for the Mars Atmosphere and Volatile EvolutioN Mission (MAVEN), and 3) introduction of Low-Density Parity Check (LDPC) coding. We report here on each of these potential upgrades, quantify the performance implications each would have on future Mars relay services in the context of future mission support scenarios, and provide a status on implementation.**

TABLE OF CONTENTS

1. INTRODUCTION

An evolving network of Mars orbiters equipped with telecommunications relay payloads has greatly increased data return from landers and rovers on the surface of the Red Planet. However, in the coming years, new landed missions will pose new challenges for the relay network, including requirements for significantly large data return and, for the first time, operational scenarios with multiple assets operating in close proximity on the surface, creating contention for relay services.

In Section 2 we summarize the capabilities of the current set of relay orbiters at Mars and describe anticipated future support scenarios. These include: support to the InSight Lander, arriving in 2018 and landing just ~500 km from Gale Crater, where the Curiosity rover continues to operate; support to the 2020 ExoMars Rover and Surface Platform, two separate collocated vehicles operating after landing in 2021, and support to the Mars 2020 rover, demanding greatly increased data return to meet its science objectives.

In Section 3 we describe the steps that have been taken to enable a "split-pass" relay capability, in which an overflight of a given pair of collocated landers can be efficiently split to provide partial relay coverage to both landed assets during that overflight. Section 4 describes options under consideration for the MAVEN orbiter's long-term extended mission relay orbit, including the use of aerobraking to reduce the orbit apoapsis and improve MAVEN's relay performance. And Section 5 describes the steps needed to fully leverage the new Low-Density Parity-Check code available on the Electra payloads onboard MAVEN and ESA's ExoMars/Trace Gas Orbiter (TGO).

Collectively, these potential improvements in the relay network offer significant new capabilities that could be essential in meeting the needs of the coming decade of Mars exploration.

2. BASELINE MARS RELAY NETWORK CAPABILITIES AND ANTICIPATED SUPPORT SCENARIOS

The in situ exploration of Mars has been greatly enhanced by the use of relay communications, allowing Mars landers and rovers to relay science and engineering telemetry via Mars science orbiters equipped with proximity link telecommunication payloads [1, 2, 3, 4]. For highly resource-constrained surface spacecraft, with limited mass, volume, and power for communication payloads, much higher data rates and aggregate data volume can be achieved on the short distance proximity link to an orbiter passing overhead, compared with transmitting data on the extremely long direct-to-Earth link back to NASA's Deep Space Network. The Mars science orbiters, with much larger transmit power and antenna aperture, can then take on the task of relay those data back to Earth.

978-1-5386-2014-4/18/$31.00 ©2018 IEEE

Table 1: Key features of the current Mars Relay Network orbiters.

	ODY	MEX	MRO	MAVEN	ExoMars/TGO
Orbit	400 km 93 deg inclination	298 x 10,100 km 86 deg inclination	255 x 320 km 93 deg inclination	150 x 6200 km 74 deg incilnation	400 km[1] 74 deg inclination
UHF Transceiver	CE-505	Melacom	Electra	Electra	Electra
Antenna	Quadrifilar Helix	Quadrifilar Helix	Quadrifilar Helix	Quadrifilar Helix	Quadrifilar Helix
Max Data Rate	256 kbps	128 kbps	2048 kbps	2048 kbps	2048 kbps
Transmit Power	12 W	8.5 W	5 W	5 W	5 W
Adaptive Data Rate Capable?	N	N	Y	Y	Y

[1]TGO orbit parameters correspond to target orbit, after completion of current aerobraking phase.

An evolving Mars Relay Network (MRN) has provided telecommunications support to a series of Mars missions, including the 2003 Mars Exploration Rovers, Spirit and Opportunity, the 2007 Phoenix lander, the 2011 Mars Science Laboratory and its Curiosity rover, and the 2016 ExoMars Schiaparelli Lander (which was lost during Entry, Descent, and Landing [EDL], but for which EDL data were captured over a relay link allowing full anomaly re-construction).

Today's MRN consists of five relay-capable science orbiters: the 2001 NASA Mars Odyssey, the 2003 ESA Mars Express, the 2005 NASA Mars Reconnaissance Orbiter (MRO), and 2013 NASA Mars Atmosphere and Volatile EvolutioN Mission (MAVEN), and the 2016 ESA ExoMars/Trace Gas Orbiter (TGO) mission. Table 1 summarizes key characteristics of these relay-equipped orbiters. The earlier NASA Odyssey and ESA Mars Express orbiters carry less capable relay payloads: Odyssey's CE-505 UHF transceiver supports a maximum data rate of 256 kbps, while Mars Express's Melacom transceiver supports rates up to 128 kbps. The more recent orbiters, NASA's MRO and MAVEN and ESA's TGO, each carry NASA's more capable Electra UHF Transceiver [5, 6], with data rates of up to 2048 kbps, with more efficient suppressed-carrier modulation, and with an adaptive data rate capability that allows the relay link rate to adaptively vary over the duration of a relay pass, based on the observed link signal-to-noise ratio, to always operate at the optimal maximum data rate as the slant range and antenna angles vary.

MRO and Odyssey are currently providing primary relay support to the Curiosity and Opportunity rovers on Mars. MAVEN has begun to provide relay service over the past year at a lower rate, while it continues its science mission, and ESA's TGO mission is in the midst of an aerobraking campaign, on schedule to achieve its final desired 400-km circular science orbit in April 2018. Figure 1 provides a summary of Curiosity and Opportunity data return over a recent three-month period. Over this representative period, the Opportunity rover – with its earlier CE-505 transceiver - returned an average of 71 Mb/sol, with roughly ~1.1 passes/sol, primarily through Odyssey. During the same period, the Curiosity rover – with its more capable Electra-Lite transceiver – returned an average of 539 Mb/sol, with an average of ~3.8 passes/sol, split roughly evenly between MRO and Odyssey, with a few additional MAVEN passes.

Looking ahead, several planned missions will introduce new challenges for the Mars Relay Network, and are driving new developments to meet those challenges. During a launch period spanning the period 5 May – 8 Jun 2018, the InSight lander mission is scheduled to launch to Mars, landing on Mars on 26 Nov, 2018, with a science objective of investigating the interior of the Red Planet. After landing, InSight will deploy two science instruments – SEIS, the first planetary seismometer, and HP[3], the Heat Flow and

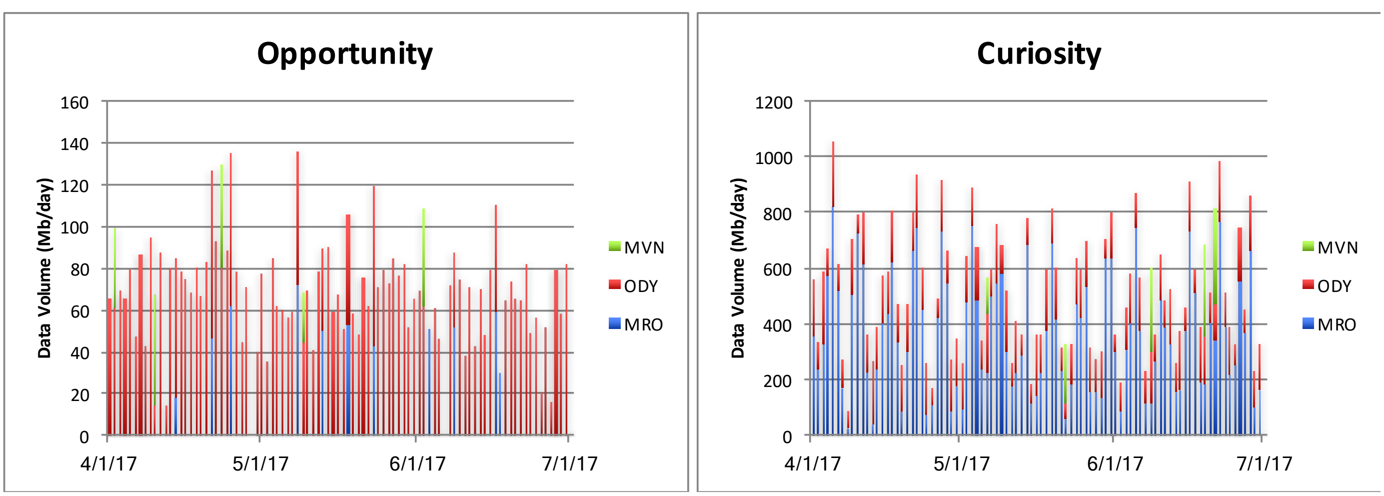


Figure 1: Mars Relay Network data return metrics from the Opportunity and Curiosity rovers during a recent three-month period (Apr-Jun 2017).

Physical Properties Probe, a robotic "mole" that will penetrate up to 5 m below the surface to measure heat flow from the Martian interior. The deployment period, lasting up to ~three months, is an operationally intensive period, where the project will want several relay passes each Martian sol, including on pass every Martian afternoon, at the end of mid-sol operations, to return decisional data that will be used to plan activities for the next Martian sol, in times to deliver commands to the lander the next Martian morning.

What will make this particularly challenging is the fact that InSight is slated to land relatively close to the Curiosity rover, currently operating in Gale Crater. Due to significant science and engineering constraints on landing site, InSight's landing site was limited to a single region roughly 500 km north of Gale Crater. This spatial surface separation is small enough that most relay overflights of the two landers have significant overlap. Because all of the existing relay orbiters can only support one pass at a time, this forces a choice between which lander is able to utilize a given overflight. This issue is particularly impactful for MRO overflights, because MRO – with its ascending node at ~ 3 PM Local Mean Solar Time (LMST) – offers mid-afternoon contact opportunities ideally times to support end-of-sol decisional data return that can be used to support next-sol activities.

In 2020, ESA plans to launch the ExoMars Rover and Surface Platform (ExoMars/RSP) mission, landing on Mars on 19 Mar, 2021 and deploying a European rover off of a Russian lander, with both vehicles carrying out independent science missions over the next 6-12 months. By definition, these two collocated spacecraft will be forced to share relay orbiter overflights. The two vehicles have an aggregate data return requirement of 400 Mb/sol.

Also in 2020, NASA plans to launch the Mars 2020 rover, arriving at Mars on 18 Feb, 2021. This Curiosity-class rover will carry a new suite of science instruments, as well as a sophisticated sampling system that will acquire a scientifically selected set of rock core and regolith samples, which will be cached on the Martian surface for potential return to Earth by future missions; in one scenario, a Sample Retrieval Lander, possibly with a smaller fetch rover, would retrieve the cached samples and launch them, in an Orbiting Sample (OS) container, into low Mars orbit. A Sample Return Orbiter would rendezvous with the OS, capture the on-orbit samples, and return them safely to Earth.

The complexity of surface operations for the Mars 2020 mission will demand highly capable relay services to enable acquisition of the suite of ~20 samples during the 1.5 Mars year primary surface mission (and ~31 total in the entire mission). Whereas Curiosity's surface mission operations was based on a requirement of 250 Mb/sol data return, Mars 2020 has established a requirement for an average of 1150 Mb/sol data return in order to support their more challenging surface operations timeline and their higher-resolution instrument suite. In addition, Curiosity has a very strong need for return of at least 120 Mb of decisional relay data at the end of each sol to support overnight (Mars time) planning for the next sol's activities.

3. SPLIT -PASS RELAY CAPABILITY

MRO's sun-synchronous near-polar orbit, with an ascending node of ~3 PM LMST, offers mid-afternoon relay contacts to low-latitude users, ideal for returning science and engineering telemetry after each sol's surface activities in time to support ground-in-the-loop planning for the next sol's activities. These passes are of high value in supporting a rapid cadence of surface operations.

When the InSight Lander arrives in Nov 2018, it will be in contention for the same afternoon MRO passes that currently support the nearby Curiosity rover. MRO's Electra payload (as well as all the current operational Mars relay payloads) provide single-access proximity links, with just one supported user at a time. To date, this has not been an issue, due to the lack of collocated landers, but the proximity of the InSight and Curiosity landing sites creates a new operational challenge. One option, of course, is to simply assign the MRO mid-afternoon overflight to one of the two landers. The issue here, though, is that the other lander will not receive an afternoon MRO pass. Odyssey's contact, with its descending node at ~6:45 PM LMST, are typically too late to support planning and command generation for the next sol, and so unless one of the other non-sun-synchronous orbiter happen to offer a mid-afternoon contact, that lander will effectively "lose" a sol's worth of productivity, having to wait two sols for ground-in-the-loop plans to reach the lander. This can have a significant impact on lander/rover productivity.

Because of this, we explored the possibility of providing a "split-pass" relay session, with back-to-back relay passes providing partial relay coverage to each landed asset, enabling both assets to obtain some amount of relay data return in the desirable mid-afternoon MRO contact opportunity. Figure 2 illustrates a representative overflight

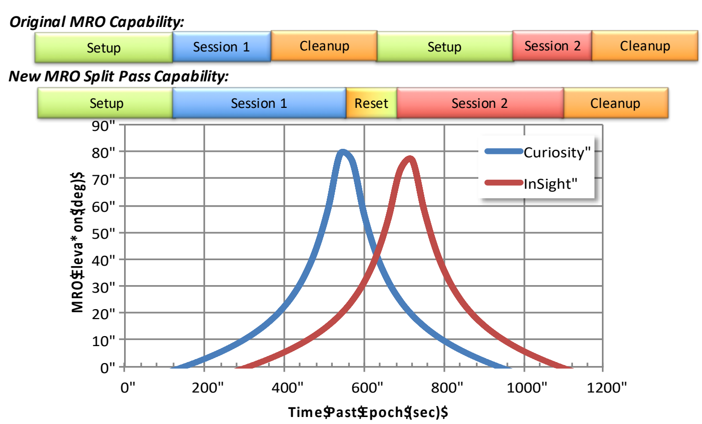


Figure 2: Timeline of achievable back-to-back relay passes for collocated Curiosity and InSight landed spacecraft, comparing the original and new expedited MRO split-pass operations scenarios

of the Curiosity and Opportunity landed spacecraft, showing the elevation angle of MRO at each of the two landing sites. With MRO near its ascending node, it rises first above Curiosity and then roughly 3 min later above InSight, ~500 km to the north. With each overflight lasting ~12 min for this high-elevation example, the view periods largely overlap.

Unfortunately, the baseline MRO operational relay capability did not support a useful split-pass function. Due to the large number of commands required to configure the Electra relay payload prior to a pass, and the large volume of engineering telemetry that needs to be offloaded from the payload after a pass, as well as the limited bandwidth of MRO's onboard 1553 bus, a given Electra relay pass had large setup and cleanup times, with a combined duration of roughly 10 min. With this large gap time, as shown in the top timeline in Figure 1, only a very small portion of each of the individual Curisoity and InSight contact periods could be supported, and these would be periods at very low elevation and thus low data rates.

To improve this situation, the MRO project developed a dedicated split-pass relay command sequence, tailored for minimizing the gap time between a pair of back-to back passes. By minimizing reconfiguration needed between passes and deferring some payload telemetry downloads until after both passes are completed, the gap time needed for resetting Electra between the two passes was greatly reduced from ~10 min down to ~2 min. This allows each landed asset to obtain a useful relay return in the mid-afternoon MRO contact opportunity, with each asset obtaining roughly half of the data it would obtain with a fully dedicated pass. This capability will be an important tool in supporting InSight and Curiosity during their simultaneous surface operations, particularly during the initial operation-intensive period of InSight instrument deployment during the first few months on the surface.

Based on this successful implementation, MAVEN and TGO are implementing similar capabilities to allow back-to-back passes with short gap times. This will offer greater operational flexibility in support InSight and Curiosity, as well as the 2020 ExoMars Rover and Surface Platform landed spacecraft, and other potential future collocated lander scenarios. Ultimately, however, future relay orbiters should assess the cost of implementing a multiple access capability, enabling simultaneous support to more than one surface asset at a time.

4. MAVEN EXTENDED MISSION ORBIT

MAVEN currently operates in a highly elliptical 150 x 6200 km orbit, with an inclination of 74 deg. This orbit was selected based on MAVEN's science objectives, enabling measurement of atmospheric loss processes at a range of altitudes, latitudes, and local times. The orbit experiences both nodal and apsidal precession, resulting in a wide range of relay overflight geometries and contact times. Passes near apoapsis operate at very large slant ranges; even though the contact times can be longer, the instantaneous data rate – which scales inversely with the square of link distance – is very low, resulting in reduced data return. In addition, MAVEN relay passes are constrained to a maximum duration of 30 min due to spacecraft energy considerations, further reducing the data return from long, high-slant-range overflights near apoapsis.

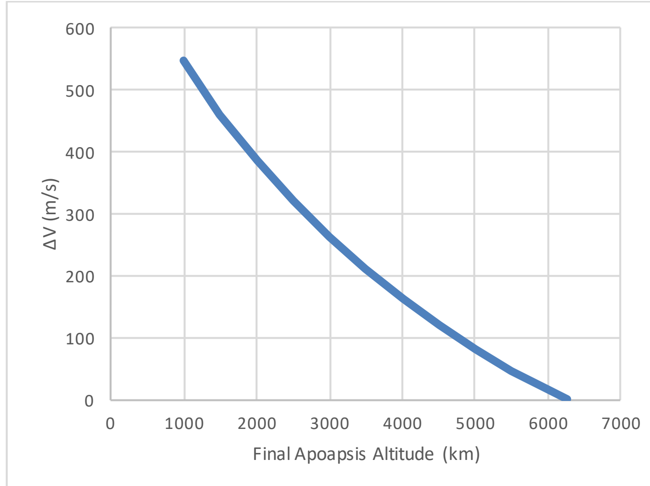


Figure 3: Propellant cost for propulsive apoapsis reduction maneuver

MAVEN completed its primary science mission in November 2015, after one full year of science operations. It is currently operating in an extended mission, continuing to fly in its primary science orbit. The low periapsis altitude of this science orbit results in significant atmospheric drag, leading to decay of the orbit, and requiring periodic propulsive maneuvers to restore the apoapsis altitude. As a result, the baseline mission plan calls for a periapsis raise maneuver when propellant reserves reach reduced levels; just a small periapsis raise up to a 230 x 6200 km orbit greatly reduces the atmospheric drag effects, enabling a much longer operation lifetime for an extended relay phase of the mission, with a goal of ensuring propellant lifetime through 2030.

To explore options for improved relay performance, the Mars Exploration Program has worked with the MAVEN project to assess options for lowering the MAVEN orbit apoapsis altitude. Achieving significant apoapsis reduction via a chemical propulsive maneuver is not feasible, given the propellant cost involved and MAVEN's remaining propellent budget. Figure 3 illustrates the cost of such a maneuver as a function of the targeted final apoapsis altitude. At the end of the current extended mission phase (Sep 2018), MAVEN is predicted to have ~220 m/s of ΔV remaining. Much of this will be required for orbit adjustments to enable coverage of Mars 2020's Entry, Descent and Landing, periapsis raise from the current 150 km altitude up to over 200 km, and ongoing orbital operations through 2030.

Table 2: Key features of current and future Mars landers impacting relay performance.

	MER-B	MSL	InSight	Mars 2020	ExoMars/RSP
Landing Site (LAT, ELONG)	Meridiani Planum (-2.1, 353.8)	Gale Crater (-4.6, 137.4)	Elysium Planitia (4.4 deg, 136.8)	Jezero Crater (18.9, 77.5)	Oxia Planum (18.3, 335.4)
UHF Transceiver	CE-505	Electra-Lite	CE-505	Electra-Lite	QineteiQ
Antenna	Monopole	Quadrifilar Helix	Quadrifilar Helix	Quadrifilar Helix	Quadrifilar Helix
Max Data Rate	256 kbps	2048 kbps	256 kbps	2048 kbps	1024 kbps
Transmit Power	12 W	8.5 W	12 W	8.5 W	5 W
Adaptive Data Rate Capable?	N	Y	N	Y	Y

An alternative approach is to utilize aerobraking to reduce the MAVEN orbit apoapsis. MAVEN was not designed like MRO to perform aggressive aerobraking as part of its nominal mission. However, MAVEN does periodically conduct science-driven "deep dips" in which its apoapsis is temporarily lowered to ~120 km, during which the orbiter can make in situ atmospheric measurements at higher densities. These deep dips are typically limited to only one week or less in duration, because the higher atmospheric drag at this lower altitude results in more rapid orbit decay. If, however, apoapsis reduction were desired, then an extended deep dip would gradually reduce apoapsis altitude at much lower propellant cost than a direct propulsive maneuver. Given that the MAVEN spacecraft was designed to support these deep dip maneuvers, this is considered a viable option for slow aerobraking down to lower apoapsis altitudes. Roughly 8 mos would be required to reach an apoapsis altitude of 1000 km; a final relay orbit of 230 x 1000 km would offer near-optimal performance in terms of mean relay data return for landed Mars missions.

However, this level of apoapsis reduction would have a significant detrimental impact on MAVEN extended mission science, as the high apoapsis altitude of the primary science orbit is designed to allow observations of solar wind-driven atmospheric escape. As a result, an intermediate apoapsis altitude of 4500 km was also considered. This altitude could be reached in just ~2.6 mos of deep-dip aerobraking, and represents a "knee in the curve" of science vs. apoapsis altitude, retaining much of the science value relative to the primary science orbit.

To support a programmatic decision on the MAVEN extended mission orbit strategy, we have carried out a comprehensive analysis of the relay performance of MAVEN in three different final orbits: 230 x 6200 km (mission baseline), 230 x 1000 km (relay optimal) and 230 x 4500 km (reduced science impact). The analysis was carried out using the Telecom Orbit Analysis and Simulation Tool (TOAST) developed at JPL [7], modeling the relay orbiter position and attitude over time, lander position, and all key telecommunication link parameters, including transmit power, antenna gains, receiver thresholds, coding and modulation schemes, available data rates, and additional factors such as Electra's adaptive data rate capability and MRO's known threshold degradation due to Electromagnitic Interference (EMI) from several of the orbiter's science instruments. Table 2 summarizes key elements of the current rovers (MER-B's Opportunity and MSL's Curiosity) as well as future landers/rovers (InSight Lander, Mars 2020 Rover, and ESA's ExoMars Rover and Surface Platform). For Mars 2020 and ExoMars/RSP, representative candidate landing sites were chosen, but these sites have not yet been finalized.

The TOAST analysis was carried out over an extended simulation period of 929 sols, with 10-sec time steps for modeling orbiter motion and overflight geometry. For each orbiter-lander geometric contact, the returned data volume was calculated based on the capabilities of the lander and orbiter transceiver. For Opportunity and InSight, with their

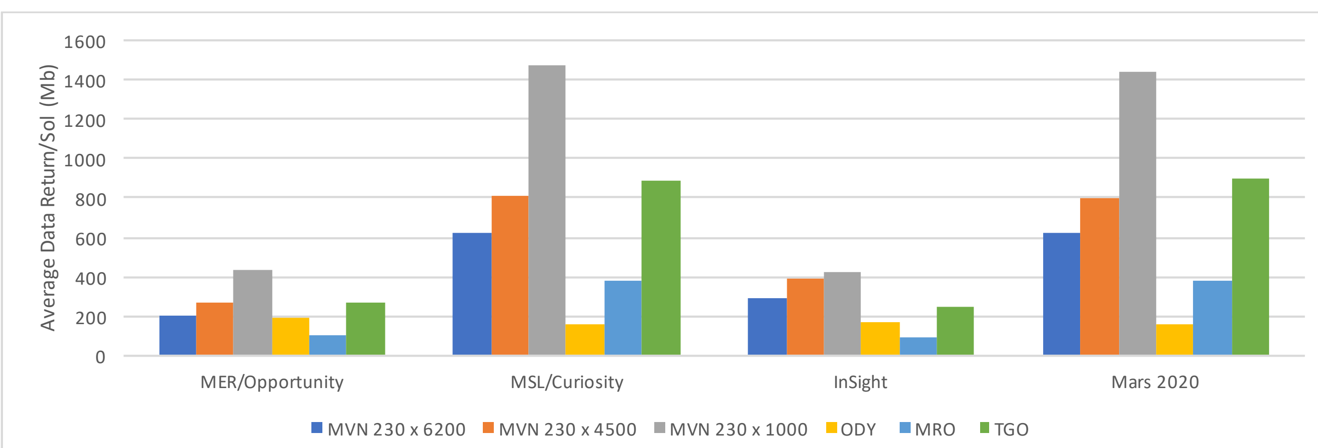


Figure 4: Mars lander/rover data return via MAVEN for three different MAVEN orbit options; data return metrics for ODY, MRO, and TGO are also shown for comparison.

earlier CE-505 UHF transceivers, only fixed data rate operations are possible; for each contact, TOAST selected the single best fixed rate to maximize data return. For the other landers and rovers, MAVEN's Electra Adaptive Data Rate function was simulated, with the link data rate varied throughout the overflight to the maximum rate possible at each point in time.

MAVEN passes were constrained to a maximum of 30 min duration, due to orbiter energy constraints. (MAVEN must re-orient the spacecraft during relay passes to point its body-fixed UHF relay antenna in the nadir direction, which steers the fixed solar arrays off of sun-point.) For geometric contacts longer than 30 min, TOAST selected the 30-min portion of the contact period that maximized the data return for that contact opportunity.

Aggregate performance metrics were based on the mean data return per sol from the best two passes available each sol. Figure 4 summarizes the data return metrics for MAVEN in each of the three candidate extended mission relay orbits; metrics for data return via ODY, MRO, and TGO are also shown for comparison. These data illustrate how aerobraking can significantly improve the performance of MAVEN as a relay asset during its extended mission. For Mars 2020 – a key future mission that is calling for increased data return – aerobraking down to a 1000 km apoapsis altitude more than doubles the average data return that MAVEN can provide, increasing from 625 Mb/sol up to more than 1.4 Gb/sol. Even in the intermediate orbit, with aerobraking terminated at an apoapsis altitude of 4500 km, the data return for M2020 increases by nearly 30%, rising above 800 Mb/sol.

A final programmatic decision on the MAVEN long-term orbit strategy will be made by NASA in the coming year, balancing the improvements in relay performance obtained by aerobraking against the impacts on MAVEN extended science. One other consideration that will be factored in is the impact of reduced apoapsis altitude on the MAVEN energy budget. As the apoapsis altitude is lowered, the fraction of each orbit that can be in eclipse increases. During certain seasons, as the orbit precesses, this can lead to insufficient insolation on the solar arrays, resulting in increased battery depth of discharge and contraints on spacecraft operations (potentially including inability to perform relay in certain seasons). This effect is currently under study, and may eliminate the 230 x 1000 km orbit option.

5. Low-Density Parity Check Coding

Forward error-correcting codes enable achieving a given bit error rate at lower a received power level or, equivalently, operating at a higher data rate for a fixed power level. All of the UHF transceivers in the current set of Mars Relay Network orbiters support Rate ½, Constraint Length 7 convolutional coding, offering roughly 5 dB of performance advantage over an uncoded link.

For the Electra UHF transceivers on MAVEN and ExoMars/TGO, we are implementing an improved forward error-correcting code offering significant additional performance improvement over the (k=7, R=½) convolutional code. Specifically, MAVEN and TGO will offer a rate ½ Low-Density Parity-Check code with a block size of k=1024, as defined in [8]. This code offers roughly a 2-3 dB performance advantage over the (7, ½) convolutional code.

Because the Electra implementation of LDPC took place prior to CCSDS standardization of the LDPC code for proximity link utilization, the current Electra LDPC decoder as implemented in the MAVEN and ExoMars/TGO flight Electra transceivers deviates from the CCSDS standard in several ways:

1) The Electra implementation uses a 78-bit sync marker that is a concatenation of six 13-bit Barker sequences (1111100110101). This is different from the latest CCSDS proposal which calls for a 64-bit sync marker with the (hexadecimal) pattern 0347 76C7 2728 95B0.

2) The Electra implementation does not incorporate randomization of the LDPC codewords, as specified in the CCSDS recommendation.

The Electra transceiver incorporates a software-defined radio architecture, enabling flight reporgramming of the transceiver after launch. Thus it is possible that these non-compliances could be corrected in a future software and firmware update to the MAVEN and TGO flight transceivers.

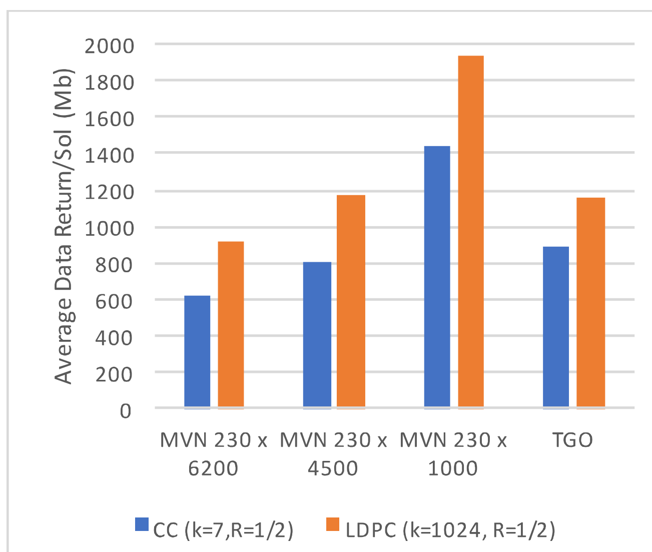


Figure 5: Comparison of average Mars 2020 data return via MAVEN and TGO, for the existing (7, ½) Convolutional Code and the proposed new Low-Densith Parity-Check code

While the LDPC decoders are already implemented in the flight radios, the Adaptive Data Rate (ADR) algorithm is not yet tailored to operate optimally with the LDPC code. ADR functions by monitoring the symbol signal-to-noise ratio (SSNR) in the symbol tracking loop on the orbiter and transmitting directives to the lander to raise or lower its data rate based on that observed SSNR value. The current implementation of ADR on the Electra orbiters is tailored for use with the (7, ½) convolutional code. The improved performance of the LDPC code enables operation of the link at lower SSNR values for the same bit error rate, so the ADR algorithm must be re-tuned for use when the LDPC code is selected.

To understand the potential benefit of this LDPC/ADR upgrade, we performed an additional TOAST simulation to compare MAVEN and TGO relay performance with and without the LDPC/ADR capability, for relay support to the Mars 2020 Rover. (Currently, only the Electra-Lite UHF transceiver offers LDPC encoding for landed assets; thus, only Curiosity and Mars 2020 are candidates for taking advantage of the LDPC benefits.) The analysis is similar in all respects to the prior analysis described in Section 4, with the sole exception of including an option to utilize the new LDPC code in place of the current (7, ½) convolutional code. The analysis assumes the ADR updates have been made to the MAVEN and TGO Electra transceivers to optimize ADR performance for both coding options.

Figure 5 illustrates the potential improvement in the average data return per sol for Mars 2020, based on selecting the two best relay passes each sol (if two or more passes are available on a given sol.) Improvements of 30-45% are observed for the LDPC coding option. (These data volume increases are slightly lower than the inherent 2-3 dB coding gain advantage due to saturation of the link at the maximum transceiver data rate; once the link has reached its maximum Electra-supported data rate of 2048 kbps, the transition to LDPC offers to advantage for that portion of the pass.) These significant data volume increases could be important in ensuring that Mars 2020 achieves the large data return needed to conduct its complex surface mission.

6. SUMMARY

A number of potential improvements in the capabilities of the Mars Relay Network have been described, offering new capabilities and enhanced performance to meet the challenges of future landed missions in the coming years:

- By implementing a split-pass relay capability, MRO can now provide back-to-back relay passes with the gap time between passes reduced from 10 min down to 2 min. This capability will allow MRO to provide critical mid-afternoon relay passes to both InSight and Curiosity, once InSight lands in November 2018, in spite of their near-collocation, and to the ExoMars Rover and Surface Platform spacecraft when they arrive in 2021. Similar capabilities are now envisioned for the MAVEN and TGO orbiters as well.
- Aerobraking offers a fuel-efficient means to reduce the apoapsis altitude of the MAVEN orbiter, with the potential for significant increases in relay performance for all supported landers/rovers. A final decision on the selected orbit strategy awaits further analysis of the impact of increased eclipse fractions on the orbiter energy budget, and will also be informed by considerations of the impact of apoapsis reduction on the quality of MAVEN extended mission science.
- A new LDPC code is available on the Electra UHF transceivers on MAVEN and TGO. Once Electra's Adaptive Data Rate algorithm is tuned to operate at the lower symbol SNR achievable with the LDPC code, additional improvements in relay performance are possible.

The combination of MAVEN aerobraking (even partially down to the 230 x 4500 km intermediate orbit) and the new LDPC code on MAVEN and TGO would allow Mars 2020 to achieve average data return of well over 1 Gb/sol via each of these Electra-equipped orbiters.

7. ACKNOWLEDGMENT

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

8. REFERENCES

[1] C. D. Edwards, "Relay Communications for Mars Exploration," *Int. J. Satell. Commun. Network*, **25** 111-145, 2007.

[2] D. Bell, et al., "MRO Relay Telecom Support of Mars Science Laboratory, Surface Operations", IEEE Aerospace Conference, Big Sky, MT 2014.

[3] N. Chamberlain, et al., "MAVEN relay operations." *2015 IEEE Aerospace Conference*. IEEE, 2015.

[4] Wenkert, D. D., Gladden, R. E., Edwards, C. D., Schmitz, P., Denis, M., & Winton, A. J. (2017). Enabling international data relay at Mars. In "Space Operations: Contributions from the Global Community" (pp. 175-205). Springer International Publishing.

[5] Charles D. Edwards, Jr., et al., "The Electra Proximity Link Payload for Mars Relay Telecommunications and Navigation," IAC-03-Q.3.A.06, 54th International Astronautical Congress, Bremen, Germany, 29 September – 3 October, 2003.

[6] E. Satorius, et al., "Chapter 2: The Electra Radio," in "Autonomous Software-Defined Radio Receivers for Deep Space Applications", http://descanso.jpl.nasa.gov/Monograph/series9/Descanso9_Full_rev2.pdf 2006.

[7] C. H. Lee, K-M. Cheung, C. Edwards, S. J. Kerridge, G. K. Noreen and A. Vaisnys, "Orbit Design Based on Global Maps of Telecom Metrics," IEEE Aerospace Conference Proceedings, Big Sky, MT, March, 2005.

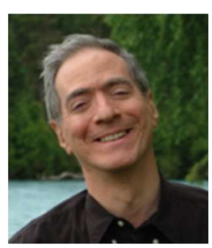
[8] TM Synchronization and Channel Coding. Issue 2. Recommendation for Space Data System Standards (Blue Book), CCSDS 131.0-B-2. Washington, D.C.: CCSDS, August 2011.

9. BIOGRAPHY

Charles (Chad) Edwards, Jr. *is the Manager of the Program Formulation Office in the Mars Exploration Directorate at the Jet Propulsion Laboratory, where he also serves as the Directorate's Chief Technologist. He received an A.B. in Physics from Princeton University and a Ph. D. in Physics from the California Institute of Technology.*

Roy Gladden *is the Manager of the Mars Relay Network Office at the Jet Propulsion Laboratory. He previously served as the Multimission Relay Operations Lead for the Mars Program Office and the Multimission Ground Systems and Services organization at JPL, and earlier led the Mission Planning and Sequencing Team for the Mars Reconnaissance Orbiter Project. He received both a B.S. and M.S. in Mechanical Engineering from Utah State University.*

Charles H. Lee *is a Professor of Applied Mathematics at the California State University Fullerton and a faculty part time staff member in the Communications Architectures and Research Section (332) at the Jet Propulsion Laboratory. He received his Doctor of Philosophy degree in Applied Mathematics in 1996 from the University of California at Irvine. Before becoming a faculty member in 1999, he spent three years as a Post-Doctorate fellow at the Center for Research in Scientific Computation, Raleigh, North Carolina, where he was the recipient of the 1997-1999 National Science Foundation Industrial Post-Doctorate Fellowship. His research has been Computational Applied Mathematics with emphases in Control, Fluid Dynamics, Smart Material Structures and Telecommunications and Biomedical Engineering.*



Daniel Wenkert *supports Mars Relay operations for NASA's Mars Exploration Program and system engineering for NASA's Multimission Ground Systems and Services office. He received an B.A. in Physics and Geology from Rice University and a Ph.D. in Planetary Science from the California Institute of Technology.*